Mantle Cloaking for Decoupling of Interleaved Phased Antenna Arrays in 5G Applications

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Abstract. The concept of mantle cloaking is applied to suppress the undesired cross-coupling among the antenna elements of two tightly spaced and interleaved phased antenna arrays used in 5G wireless applications, which in turn enhances the radiation characteristics of the arrays. It is demonstrated that the specifically designed metasurface cloaks decouple the antenna elements of two different arrays and enable to restore the original radiation patterns of the isolated arrays, such that the antenna arrays placed in close proximity of each other can radiate independently for a wide range of beam scanning angles. This paper illustrates microstrip antenna arrays with elliptically shaped metasurface cloaks integrated in printed technology. The simulation results validate the fact that by encasing the elements of the arrays with their respective cloaks, it is not only possible to eliminate the cross coupling but also to restore the radiation properties of the antenna arrays within the frequency bands of their operation.

INTRODUCTION

Phased antenna array systems are widely used by virtue of their high gain and directivity. Predominantly, phased arrays, designed in various configurations: linear, planar, and conformal, have been used for beam steering in military and industrial applications [1]. There is an ever increasing demand in wireless communication capacity which necessitates the accommodation of densely packed antenna arrays in a very compact system, for various applications such as MIMO, radar detection, mobile communications, etc. However, designing multiple arrays in a compact area with a small separation between array elements is not only arduous but it also results in the deterioration of the radiation patterns of the array elements. This is due to cross-coupling between such closely packed antennas, wherein the elements of one array are affected by the presence of the elements of the other array and vice versa. To address this issue, recently, there has been an increased interest in the study of electromagnetic invisibility realized with metamaterials, due to its vast significance and potential applications in camouflaging, non-invasive probing, and low observability, among others. Alternative approaches to metamaterial cloaking include the plasmonic cloaking [2] and cylindrical transmission-line cloaking [3], [4]. A common trait in all of the above mentioned cloaking techniques is that bulk volumetric metamaterials are utilized, which are difficult to realize and have a finite thickness often comparable with the size of the region to be cloaked.

To overcome the aforementioned problem, a different cloaking technique based on the concept of mantle cloaking [5]-[10] has been proposed that causes an object to be electromagnetically invisible. This technique is based on the principle of scattering cancellation, wherein an ultra-thin metasurface creates anti-phase surface currents resulting in the suppression of the dominant scattering mode of the object to be cloaked. The engineered metasurfaces produce a cloaking effect such that the neighboring antennas do not sense each other [11], [12]. Inspired by the mantle cloaking of elliptical cylinders, in particular 2-D metallic strips, this concept has also been extended to free-standing strip dipole antennas [13] and microstrip monopoles in printed technology [14], [15] at microwave frequencies. It has been shown that the metasurface cloaks not only reduce the mutual coupling between closely spaced antennas but also enable to restore their original radiation patterns. The concept of decoupling two printed monopoles is presented in [13] and has been experimentally verified in [16]. Very recently, the concept of decoupling and cloaking has also been applied to interleaved arrays of free-standing strip monopoles at microwave frequencies [17].

In this paper, we have applied the concept of cloaking and decoupling to two closely spaced, interleaved microstrip monopole antenna arrays in printed technology, which are designed to operate at two different frequency bands. Through the simulation results, it is demonstrated that the individual array elements are decoupled from each other. Along with this, it is also observed that their beam patterns are restored as if they were two isolated arrays. This is possible owing to the fact that the elliptical metasurface cloaks around the elements of the array act as filters, so as to make the elements of the individual arrays poor radiators at the operating frequencies of each other. Consequently, a fixed array size, which is traditionally used for only one array, can now be allocated to two distinct interleaved arrays, potentially leading to large cost reduction in practical applications and can be installed on platforms with compact space. Concurrently, it also enables frequency diversity. The design procedure and all the numerical full-wave simulations presented in this paper are obtained with the CST Microwave Studio [18].

DECOUPLING AND CLOAKING OF INTERLEAVED PHASED ANTENNA ARRAYS

In this paper, we investigate phased, linear arrays of microstrip monopole antennas consisting of four identical modules stacked vertically along the x-axis (Figure 1-a). Each module of the arrays comprises of a dielectric substrate (L=7.5 mm, W=6.75 mm, h=0.13 mm, and ε_r=2.2), which hosts two printed monopoles – Antenna I and II designed for frequency bands f_1=28 GHz and f_2=39 GHz, respectively (Figure 1-b). The two antennas are separated by a distance of 2.42 mm (which is either 0.226 λ_1 or 0.315 λ_2, where λ_1 and λ_2 are wavelengths at the frequencies f_1 and f_2, respectively). The ground plane dimension is G=1.8214 mm. The consecutive modules in the array are spaced by d= 0.5 λ_1 (in mm) distance apart and the elements of each array is fed with currents of equal amplitude and phase. The schematic of the uncloaked interleaved arrays is shown in Figure 1-a.

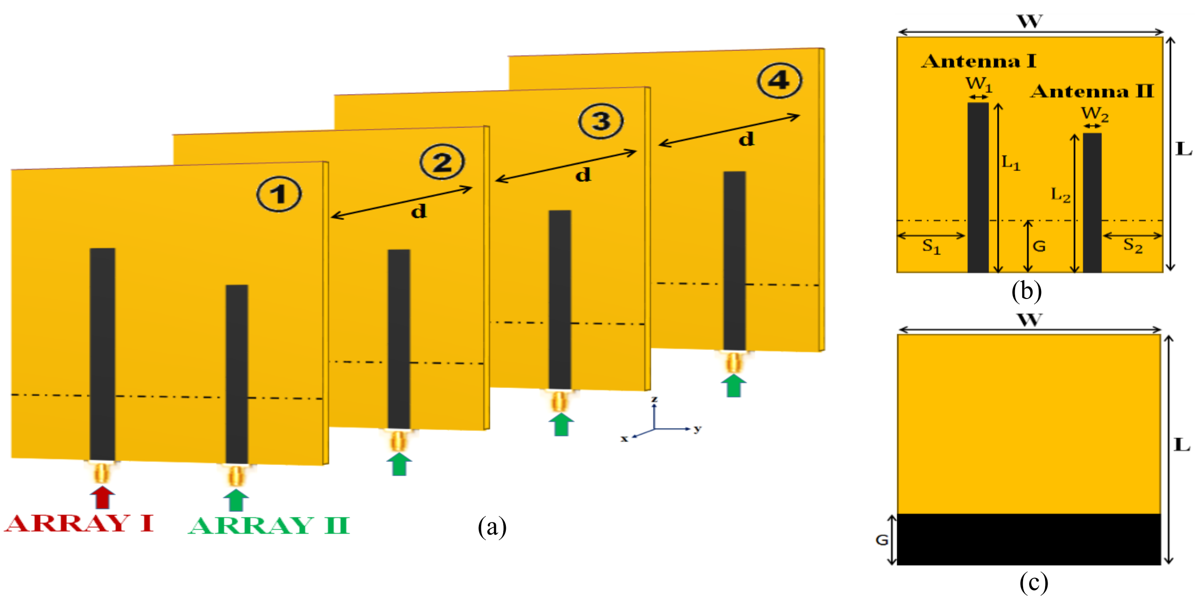

FIGURE 1. (a) Arrays configuration of uncloaked printed monopoles stacked along the x-axis, (b) Front-view, and (c) Back-view of a single module of printed monopoles on a substrate of thickness h, operating at f_1=28 GHz and f_2=39 GHz.

Now, the elements of the two arrays are placed in close proximity of each other, and thus, the radiation pattern, matching properties and, accordingly, the total efficiency of both the arrays will be affected due to spatial interference. It follows that when two arrays are closely packed, the neighboring antenna elements of the arrays are strongly coupled, deteriorating the constructive far-field coupling (array gain). In the following, we explore how to minimize this effect in such a way that the interleaved arrays operate independently from each other as if they are isolated. It has been demonstrated in [13] that the elliptical metasurface cloaks enable to reduce the mutual coupling effect between the two printed monopole antennas. Employing similar approach for our array configuration, the array elements are enveloped by elliptical cloaks explicitly tailored for the individual monopoles. It is to be noted that the single module of the array was initially designed to operate for frequency bands 28 GHz and 39 GHz, respectively. However, for the array configuration, a slight frequency shift was observed for the antennas at 39 GHz (shifted to approximately 38 GHz) and the results so obtained are consistent at the frequency band of 38 GHz. So, in this paper, array of Antenna II is referred to as array operating at 38 GHz.

For the configuration under consideration, we examine three cases: (a) Isolated Array I (in the absence of antenna elements of the Array II), (b) Isolated Array II (in the absence of antenna elements of the Array I), and (c) Coupled arrays (where elements of Arrays I & II are placed in the vicinity of each other). The above mentioned cases are evaluated for both uncloaked and cloaked conditions so as to manifest that appropriately designed elliptical metasurfaces decouple the two interleaved arrays and facilitates restoration of their gain patterns (Figure 3), considering the fact that the dominant coupling is the cross-coupling between an element from the Array I and its respective neighboring element from the Array II. The schematics of cloaked interleaved arrays are illustrated in Figure 2.

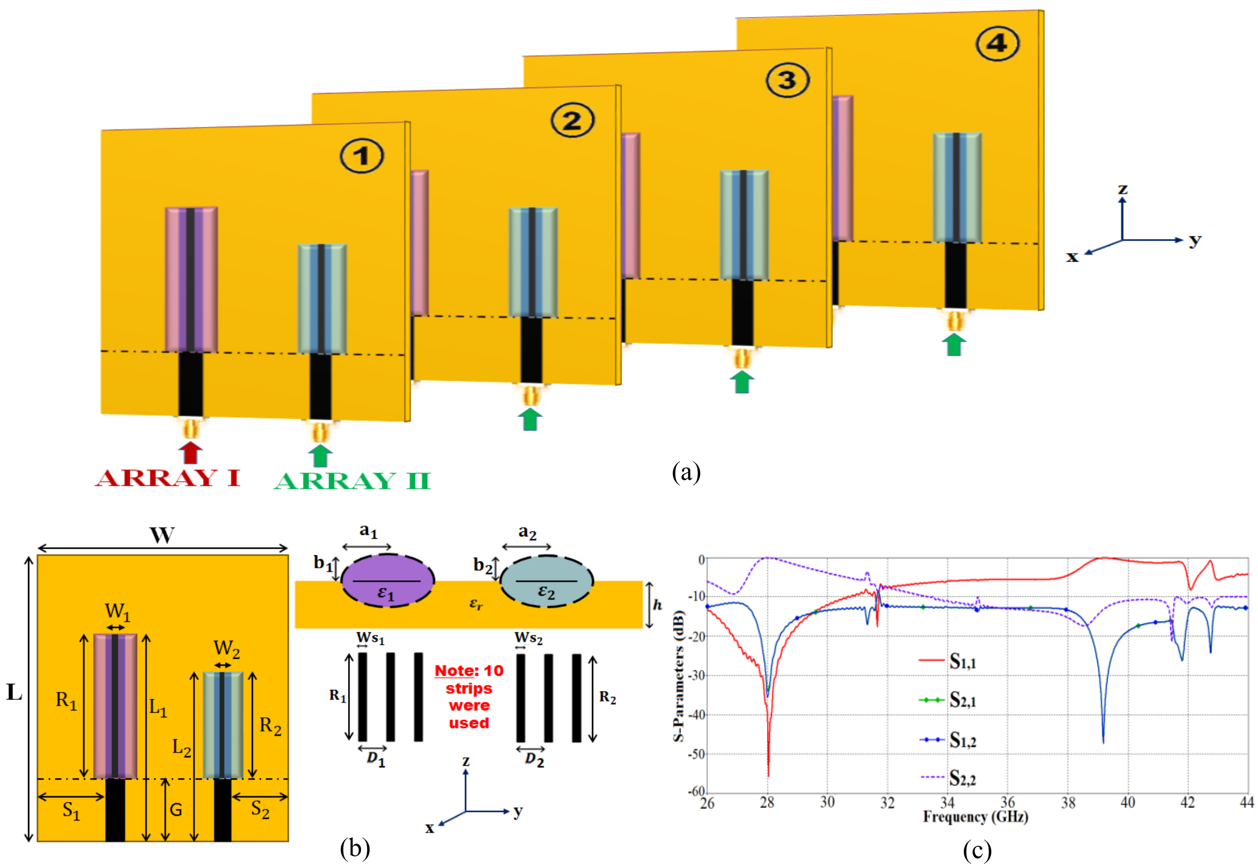

FIGURE 2. (a) Cloaked printed monopole arrays stacked along the x-axis, (b) Front-view and cross-section-view of a single module, and (c) S-parameters plot for single module of cloaked printed monopoles demonstrating decoupling of antennas.

The array elements and the metasurface cloaks are designed using the following parametric values: L_1=3.81 mm, W_1=0.428 mm, S_1=2.089 mm, R_1=1.9896 mm, Ws_1=0.0375 mm, a_1=0.2357 mm, b_1=0.0982 mm, ε_1=3.73, D_1=0.1094 mm, L_2=3.39 mm, W_2=0.308 mm, S_2=1.5 mm, R_2=1.5686 mm, Ws_2=0.0231 mm, a_2=0.1692 mm, b_2=0.0705 mm, ε_2=12.51, and D_2=0.0785 mm. It can be seen from the S-parameters plot in Figure 2-c that the metasurface cloak encased around Antenna I makes it a poor radiator at the resonant frequency band of Antenna II and vice versa, thus decoupling them and enabling them to radiate independently.

Using the 3-D gain patterns shown in Figure 3, we manifest that the metasurface cloaks recover the gain patterns of the arrays in such a way that it seems they are radiating independently. As seen in Figures 3-b and 3-e, the realized gain patterns for Arrays I and II (operating at frequency bands f_1=28 GHz and f_2=38 GHz, respectively) are distorted in the absence of cloaks, when both the arrays are placed in close proximity of each other (uncloaked coupled case). However, when the individual elements of both the arrays are enveloped by their corresponding metasurface cloaks (cloaked decoupled case), restoration of the gain patterns is observed (Figures 3-c and 3-f for Arrays I and II, respectively); the gain patterns are very much similar to the patterns of the isolated cases. This is evident from the 3-D gain patterns shown for the case of isolated Array I and II in the Figures 3-a and 3-d, respectively.

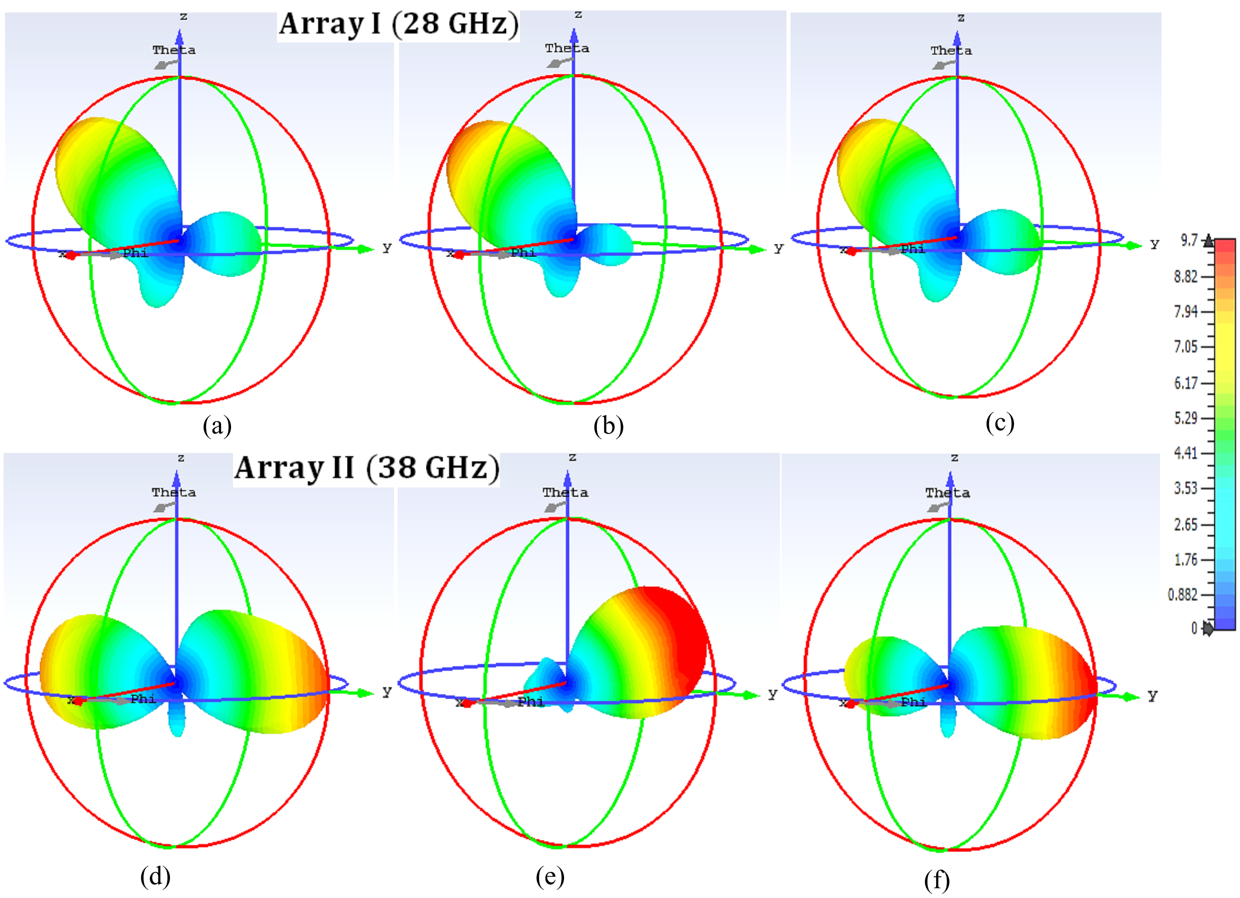

FIGURE 3. 3-D gain plots for (a) Isolated Array I (frequency band 28 GHz), (b) Uncloaked Coupled Arrays, (c) Cloaked Decoupled Arrays for the case where Array I is active, (d) Isolated Array II (frequency band 38 GHz), (e) Uncloaked Coupled Arrays, and (f) Cloaked Decoupled Arrays for the case where Array II is active.

Arrays are designed with the objective of achieving higher gains. The polar plots for the array configuration, depicting realized gain of array I and array II in the two planes: $\Theta = 90^0$ and $\Theta = 0^0$, are illustrated in Figure 4. From the polar plots, it is seen that the realized gain of Array I is approximately 7 dBi (Figure 4-a) and that of Array II is approximately 9 dBi (Figure 4-c) in the broadside direction for the isolated cases. For the uncloaked coupled cases, the gain plots for both the arrays are altered significantly. These alterations in the realized gain plots observed for uncloaked scenarios are recovered almost completely for the case when antenna elements of both the arrays are cloaked with their respective metasurfaces, such that they resemble the plots for the isolated arrays. These polar plots thus serve to substantiate the fact that the metasurface cloaks designed for the individual antenna elements facilitate restoration of the radiation characteristics of the arrays.

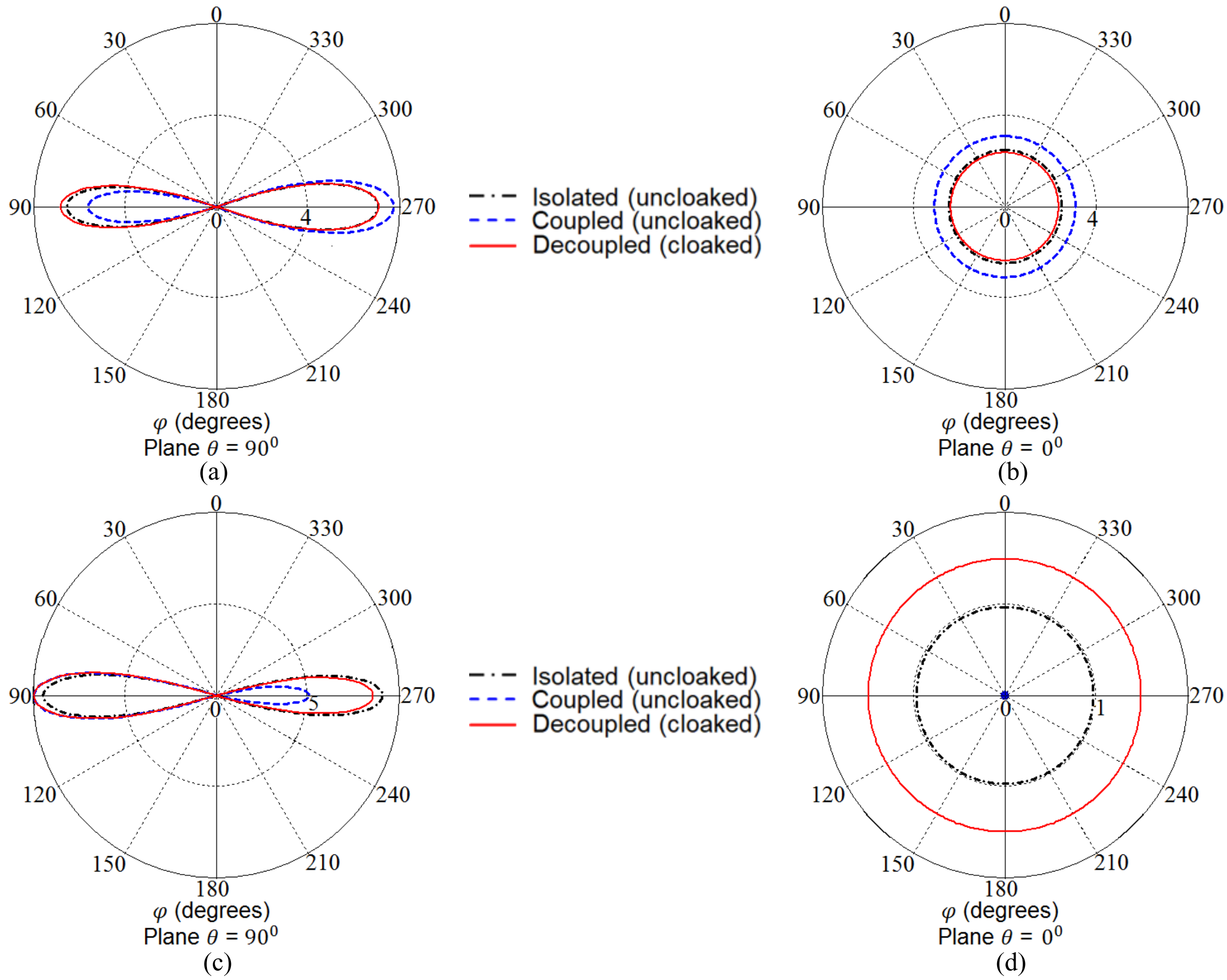

FIGURE 4. Polar plots for (a) Array I (frequency band 28 GHz) for plane $\Theta = 90^0$, (b) Array I for plane $\Theta = 0^0$, (c) Array II (frequency band 38 GHz) for plane $\Theta = 90^0$, (d) Array II for plane $\Theta = 0^0$.

We further proceed on to demonstrate the decoupling effect of the metasurface cloaks through the snapshots of electric field distribution for the arrays in the near-field (Figure 5) as well as the far-field (Figure 6). In Figure 5-a, Array I is active (ports 1, 3, 5 and 7 are excited) whereas Array II is kept passive and in Figure 5-c, Array II is active (ports 2, 4, 6 and 8 are excited), whereas Array I is kept passive. In both these cases, arrays are uncloaked and hence, cross-coupling between elements of the arrays is observed, which enables the power to be coupled to the port of the neighboring antenna through the microstrip feed line. On the other hand, the presence of the metasurface cloaks reduces the field interaction between the antennas by making the radiating parts of the antennas invisible to each other. As a result, the electric field produced by one array element is not sensed by the input port of the neighboring array element. As indicated by the Figures 5-b (where Array I is active) and 5-d (where Array II is active), the moment the radiating parts of the antennas are cloaked, due to the nature of the mantle cloaking method (wherein anti-phase surface currents are produced by the cloak structure), the induced surface currents owing to the mutual coupling effect between array elements, are canceled by anti-phase currents developed by the elliptically shaped metasurfaces and will not reach the input port of the neighboring antenna. The far-field electric-field distribution shown in Figure 6 also validates the decoupling effect of the metasurface cloaks. Figure 6-a shows comparison for different cases of the field plots when Array I is active and Array II is inactive. Similarly, comparison for various scenarios of the field plots when Array II is active, keeping Array I inactive is shown in Figure 6-b. The plots in Figure 6 show distinct coupling for uncloaked coupled case whereas the mutual coupling is negated when the antenna elements are enveloped by the suitable metasurface cloaks; thus illustrating the decoupling effect and thereby ensuring constructive far-field coupling.

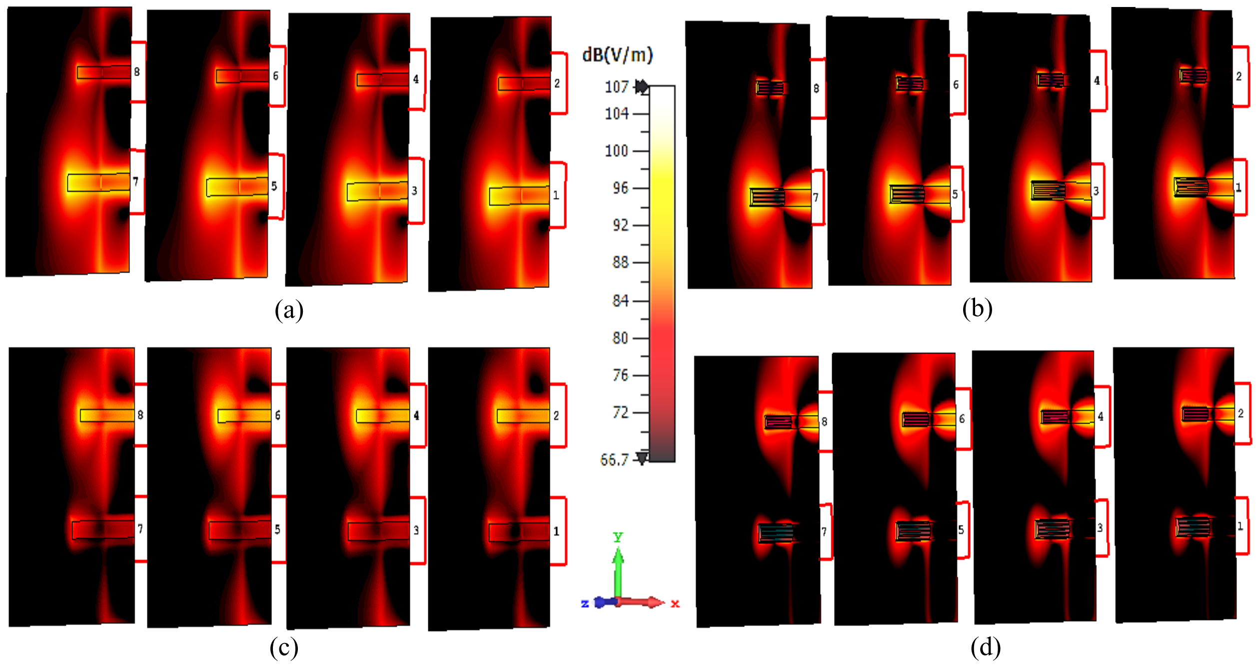

FIGURE 5. Near-field electric field distributions for the arrays: (a) Uncloaked case, (b) Cloaked case when Array I (frequency band 28 GHz) is active, (c) Uncloaked case, and (d) Cloaked case when Array II (frequency band 38 GHz) is active.

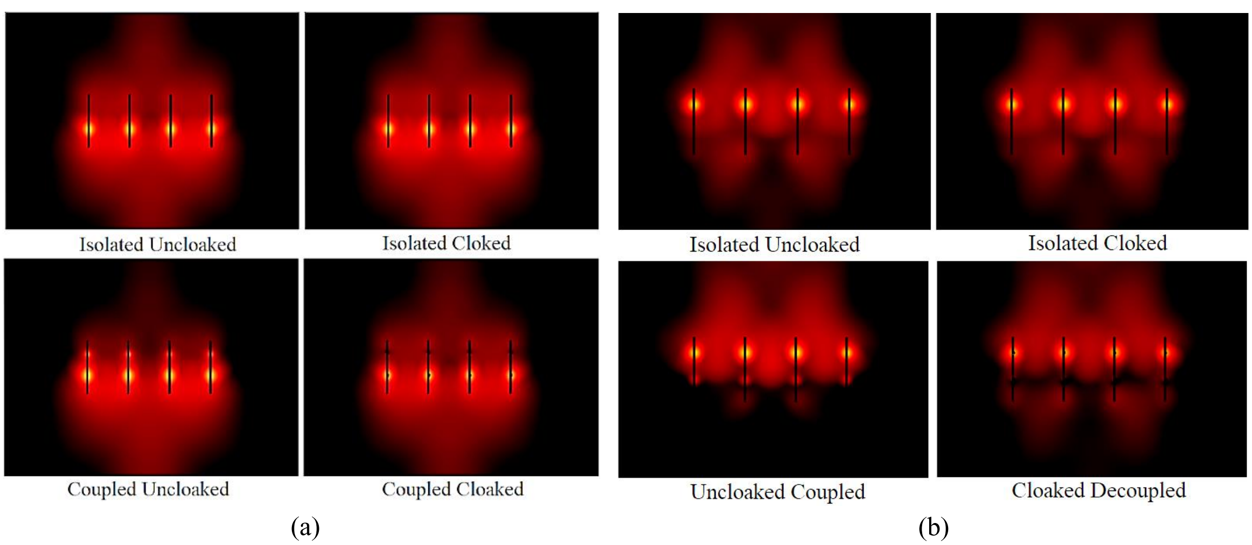

FIGURE 6. Far-field electric field distribution (a) Array I (frequency band 28 GHz) is active, (b) Array II (frequency band 38 GHz) is active.

Also, the total efficiencies of both the arrays for uncloaked as well as cloaked cases are plotted in Figure 7. It is clearly seen that by cloaking the antennas with the specifically designed elliptical metasurfaces, the total efficiency of one array is reduced significantly at the resonance frequency of the other array and may be improved at its own resonating frequency. It is of paramount importance that the metasurface cloaks do not deteriorate the efficiency of the antenna element which it envelops; rather its effect should be reflected at the frequency of the other antenna element placed in its vicinity. Subsequently, one array becomes a poor radiator at the frequency of the neighboring array, at the same time, radiates in a similar fashion as the isolated case at its own resonant frequency. Evidently, the presence of the metasurfaces leads to the suppression of the far-field coupling between the arrays.

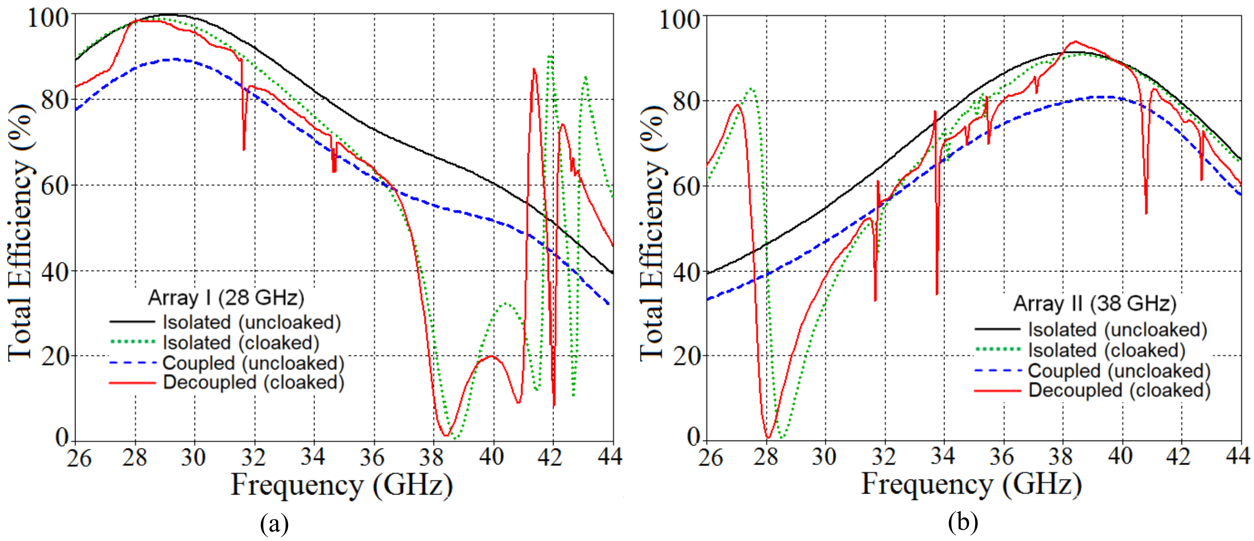

FIGURE 7. Total efficiencies for (a) Array I (frequency band 28 GHz) and (b) Array II (frequency band 38 GHz).

CONCLUSION

In this paper, we have proposed an approach based on the utilization of the mantle cloaking method, which facilitates the use of engineered elliptical metasurfaces in order to make the antenna elements of two closely spaced linear printed monopole arrays, invisible to each other. In this regard, it has been demonstrated by the simulation results presented in the paper that by encompassing antenna elements with appropriately designed confocal elliptically shaped metasurface cloaks, it is possible to negate the cross coupling between the elements of Array I and II when they are in close proximity of each other. Consequently, the destructive effects on the radiation properties of the antennas are prevented and the gain patterns are reinstated in a manner that it seems the array elements do not sense the presence of each other, thus radiating independently. Hence, in this paper, we have endeavored to present a design that will lead to densely packed arrays with improved performance and beam scanning capabilities (the results for beam scanning will be given in the presentation).

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